Investigation of Possible Dark Matter Direct Detection in Electron Accelerators

Junji Hisano,[1] Minoru Nagai,[1] Mihoko M. Nojiri,[2] and Masato Senami[1]

[1]*ICRR, University of Tokyo, Kashiwa 277-8582, Japan*
[2]*YITP, Kyoto University, Kyoto 606-8502, Japan*

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We investigate a possibility of neutralino dark matter (DM) direct detection in the future electron accelerators. That is counting of high p_T electron recoil events by neutralinos in halo. If selectron and neutralino masses would be precisely measured in future collider experiments, the beam energy could be tuned so that the scatterings are dominated by on-pole selectron exchange. When selectron and neutralino mass difference is smaller than $O(10)$ GeV, the elastic cross section exceeds over micro barn. Discovery of the high p_T electron events would be a firm prove of the neutralino DM component in halo. In the experiment, the electron beam energy must be tuned within $O(10)$ MeV and the electron beam with high currents of $O(100)A$ is required for the detectors of the total length of a few hundred meters so that the sufficient event rate is obtained. The dependence of the event rate on the DM velocity distribution in halo is also discussed. This method might be applicable to other DM candidates.

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Nature of the dark matter (DM) in the universe is an important problem in particle physics, astronomy and cosmology. The lightest neutralino, $\tilde{\chi}^0$, in the minimal supersymmetric (SUSY) extension of the standard model (MSSM), is a good DM candidate since the lightest SUSY particle (LSP) is stable due to the R parity [1]. The cosmological DM abundance, which is now precisely measured by the WMAP [2], constrains properties of the neutralino and the SUSY particle mass spectrum if the DM is generated in the hot thermal bath in the early universe [3].

The neutralino works well as the cold DM in the structure formation in the universe. High resolution N-body simulations show that the cold DM hypothesis explains well the large structure of our universe [4]. On the other hand, the DM distributions in smaller scales than $O(1)$ Mpc are still unresolved. The local DM abundance and the DM velocity distribution on the neighborhood of the solar system are also not well constrained from the rotation curve measurements. The direct DM detection on the earth and the indirect detection of anomalous cosmic rays produced by the DM annihilation may give clues to the problems.

The conventional DM direct detection relies on nuclear recoil in nuclei-DM elastic scattering. The sensitivities of the proposed experiments cover a significant part of the MSSM parameter space. However, to evaluate the local DM density and velocity distribution from the counting rates, precise determination of the hadronic matrix elements is necessary. The cross section also depends on various SUSY parameters such as relatively suppressed Yukawa coupling of strange quark (or $\tan\beta$), heavy Higgs mass and Higgs-neutralino-neutralino coupling and so on. To this end, positive signals in the direct detections may not necessarily prove whether the DM is the neutralino since they merely measure the DM-nuclei scattering cross section.

The nature of the LSP would be measured if the SUSY particles are discovered in future high energy colliders. This is because the LSP will be copiously produced from the cascade decays of the heavier SUSY particles. The LHC experiment is scheduled to start on 2007, and squarks and gluino with masses up to 2.5 TeV can be discovered. Furthermore, the interaction of the lightest neutralino would be also measured at the LHC [5] and a future linear collider (LC) [6]. While they might be successful to determine the thermal relic density of the universe and provide consistency checks of the neutralino DM assumption, it relies on the assumptions that the neutralino is stable in the cosmological time scale and the thermal history of the universe follows the standard big bang scenario. It is important to observe the neutralino DM in more direct and less ambiguous ways.

In this paper we investigate a possibility of direct neutralino DM detection which might be realized in the future electron accelerators. The electrons in the beam can interact with the DM neutralinos in our neighborhood. The electron-neutralino elastic scattering is induced by the s-channel exchange of selectrons $\tilde{e}^-$, which are superpartners for electron, in addition to the t-channel Z gauge boson exchange. If the beam energy would be tuned to the difference between the neutralino and selectron masses (Δm), the elastic scatterings between the DM neutralinos and the beam electrons are dominated by on-pole selectron exchange and the cross section is suppressed only by square of Δm. Building of such an electron beam might be considered when the mass difference is precisely measured in the future collider experiments such as LC experiments.

If a high intensity electron beam would be available, one could determine the nature of the DM without any ambiguities by detecting on-pole production of selectrons, because the measurement proves that the DM is the neutralino LSP. Note that the relevant couplings would be directly measured at LC when selectron productions are accessible. Therefore, the DM physics that

might be explored by a high intensity electron beam is unique. However, one needs several technical breakthroughs to realize it. We clarify the requirements to the electron beam and detectors in this paper. It is also shown that the number of events might have a sensitivity to the DM velocities when the selectron decay width is suppressed by the mass difference or the coupling. This implies that if there would be enough statistics, the DM velocity distribution in the halo and the DM wind due to a circular motion of the solar system might be constrained by this experiment.

First, let us discuss the elastic scattering process between electrons in the beam and the DM neutralinos and evaluate the expected number of events. The DM neutralinos are highly non-relativistic in the universe, and the local DM velocity in our neighborhood is typically $v \sim 10^{-3}c$. When the beam energy, $E_{\rm beam}$, would be tuned as $E_{\rm beam} = \overline{E}_{\rm beam}$ with $\overline{E}_{\rm beam} \equiv (m^2_{\tilde{e}^-} - m^2_{\tilde{\chi}^0})/(2m_{\tilde{\chi}^0})(\simeq \Delta m)$, the process is dominated by the on-pole selectron exchange. In this case the spin-averaged differential cross section with respect to the angle between the beam and the recoiled electron, θ, is given as

$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi}{(m^2_{\tilde{e}^-} - m^2_{\tilde{\chi}^0})^2}\frac{m^4_{\tilde{e}^-}}{m^2_{\tilde{\chi}^0}}\frac{(m_{\tilde{e}^-}\Gamma_{\tilde{e}^-})^2}{(s-m^2_{\tilde{e}^-})^2 + (m_{\tilde{e}^-}\Gamma_{\tilde{e}^-})^2} \times(1+A(\cos\theta))^{-2} \tag{1}$$

with s square of the center-of-mass energy and $\Gamma_{\tilde{e}^-}$ the selectron decay width. Here, the function $A(\cos\theta)$ is defined as

$$A(\cos\theta) = \frac{m^2_{\tilde{e}^-} - m^2_{\tilde{\chi}^0}}{2m^2_{\tilde{\chi}^0}}(1-\cos\theta), \tag{2}$$

and the energy of the recoiled electron, $E_{\rm recoil}$, is also given by it as

$$E_{\rm recoil} = E_{\rm beam}(1+A(\cos\theta))^{-1}. \tag{3}$$

When $\tilde{\chi}^0$ is bino-like, the selectron decay width is

$$\Gamma_{\tilde{e}^-} = \frac{g_Y^2 Y^2}{8\pi}(O_{11})^2\frac{(m^2_{\tilde{e}^-} - m^2_{\tilde{\chi}^0})^2}{m^3_{\tilde{e}^-}} \tag{4}$$

where Y is the hypercharge for $\tilde{e}^-$ and O_{11} is the neutralino mixing matrix element. For simplicity, we take $O_{11} = 1$ and $Y = -1$ for the right-handed selectron in the following. In this case

$$\Gamma_{\tilde{e}^-} = 20\ \text{MeV} \times \left(\frac{\Delta m}{10\text{GeV}}\right)^2\left(\frac{m_{\tilde{e}^-}}{100\text{GeV}}\right)^{-1}. \tag{5}$$

When the neutralino and selectron masses are close to each other, we find from Eq. (1) that the cross section at $E_{\rm beam} = \overline{E}_{\rm beam}(\simeq \Delta m)$ is suppressed only by $(\Delta m)^2$. If the DM velocity dependence of the cross section is negligible, the expected number of events, N, is

$$N = 73 \times \left(\frac{\Delta m}{10\text{GeV}}\right)^{-2}\left(\frac{m_{\tilde{\chi}^0}}{100\text{GeV}}\right)^{-1}\left(\frac{\rho_{\rm DM}}{0.3\text{GeV/cm}^3}\right) \times\left(\frac{j}{100A}\right)\left(\frac{T}{1\text{ year}}\right)\left(\frac{L}{1\text{ km}}\right). \tag{6}$$

Here, j is the beam current, L the detector length, and T the duration of experiment. We fix the local DM mass density, $\rho_{\rm DM}$, to be 0.3GeV/cm^3 in this paper. If the beam can be polarized, the expected number of events is multiplied by a factor two. This elastic scattering process is also noticed in an earlier work in Ref. [7].

When $\Delta m/m_{\tilde{\chi}^0} \ll 1$, the elastic cross section can be enhanced if the beam energy could be tuned to $\overline{E}_{\rm beam}$, however, the requirements for the DM direct detection in electron accelerators would be severe. We now discuss the requirements to observe such events in order.

First, for our purpose, the neutralino and selectron masses and the coupling have to be measured with sufficient precision at the earlier collider experiments so that $\overline{E}_{\rm beam}$ and $\Gamma_{\tilde{e}^-}$ are determined. Especially, the uncertainty of $\overline{E}_{\rm beam}$ must be smaller than $\Gamma_{\tilde{e}^-}$. Otherwise, the beam energy could not be tuned, so that the elastic process between the DM neutralinos and the beam electrons is not dominated by the on-pole selectron exchange. This implies from Eq. (5) that $\overline{E}_{\rm beam}$ should be determined at least with precision of $O(10^{-3})$ for $\Delta m/m_{\tilde{\chi}^0} = 10\%$.

At the LHC, the mass difference between the neutralino and sleptons might be measured with the error on the order of a few GeV by using the events with lepton-antilepton pair for favorable parameters [8]. The LC would be able to measure the absolute LSP and slepton masses with the error $O(50)$ MeV using the threshold scan and the end point measurements [9]. The error for the mass difference Δm, determined by the end point measurement, may be even smaller. When the beam energy spread is a dominant uncertainty in determination of Δm, Δm might be determined with the precision of 10^{-3} at the LC. The neutralino interaction would be also measured precisely at the LC so that the selectron decay width might be determined.

Next is the requirements for the electron beam. The energy spread of the electron beam must be less than $O(10^{-3})$ for $\Delta m/m_{\tilde{\chi}^0} = 10\%$ by the same reason as for the determination of $\overline{E}_{\rm beam}$. In addition, very high currents are required in our proposal as seen in Eq. (6), which is about 10 times higher than that for the currently proposed Super B factory.

In the KEKB at KEK, which is an asymmetric electron-positron collider for B physics, the averaged beam currents in the low energy positron (3.5 GeV) and high energy electron rings (8.0 GeV) are $1.861A$ and $1.275A$, respectively. The PEP-II at SLAC also has comparable currents. Now upgrade of the KEKB to the SuperKEKB is proposed, aiming for the beam currents 9.4 and $4.1A$ [10]. While the energy spreads of these accelerators are smaller than 10^{-3}, their beam currents are not

much enough for our purpose.

The beam focusing at the interaction point is the sources of the beam instability in collider experiments with high luminosities. For the DM direct detection in electron accelerators, it would not be a serious problem since the beam focusing is not required. Rather, the synchrotron radiation (SR) from the electron beams would bound the beam currents. The SR at the arc sections of the accelerators may damage the beam pipe and also causes the beam power loss.

A hint to solve this problem may be in a technology called Energy Recovery Linac (ERL) [11]. In this scheme, the electron beam energy is lowered by transferring the energy to the RF power, and the power is used to accelerating the electron beam again. The principle of the ERL technology have been tested at Thomas Jefferson National Accelerator Facility [12]. Various facilities using the ERL technology, such as photon factories, electron cooling and so on, are proposed. If it would be possible to have a storage ring where the beam energy is lowered before the arc section to keep the beam power in the RF for accelerating the electrons in the straight section, one could achieve the high current electron beam with less power consumption [20].

Even if an electron beam of $O(100)A$ is possible, the number of events would be only around 1 event/10m/year for mass difference of the order of 10 GeV. Note that because this is a fixed target experiment where the target is on the beam line, many detector units should be placed along the beam line. The total length must be as long as 300 m$-$1 km. This means that each detector units should be as simple as possible.

We note that the signal events should be distinguished over the backgrounds (BGs). When $\Delta m/m_{\tilde{\chi}^0} \ll 1$, the recoiled electrons in the signal events have energies between $E_{\rm beam}(1-2\Delta m/m_{\tilde{\chi}^0})$ and $E_{\rm beam}$ and large transverse momentums. This is because $A(\cos\theta)$ in Eq. (2) is suppressed by $\Delta m/m_{\tilde{\chi}^0}$ and the angular distribution of the signal electron is almost spherical. Furthermore, the momentums of the signal electron must be pointing to the beam line. The kinematics of the signal events is well-constrained.

The signal electrons would be detected by placing either electromagnetic calorimeter or tracking chamber with solenoid magnets along the beam line. The expected BGs would come from either cosmic rays or the beam interaction. To remove accidental cosmic ray BGs, we need a reasonable resolution for electron tracks to reject any tracks crossing the beam line from outside of the detector.

Other BGs are electrons scattered by the beam gas. They could be reduced by measuring the electron momentums since the BG electrons are forward-going and $p_T \ll E_{\rm beam}$. The electron momentum perpendicular to the beam axis can be measured precisely with magnetic fields, while the resolution of the electron momentum along the beam axis would be much worse than that in ordinary wire chambers.

Since the magnetic field along a long detector will destabilize the beam, the detector should be divided to short segments along the beam line so that the direction of the magnetic field in the each segment is reversed to the next segment. This segmentation would also suppress the BG electrons due to pile up from the upper currents, and the background level might be lowered.

π^-s produced from photo-nucleon interactions in the beam pipe would be also a source of the BGs. They are even more low energy compared to the electrons from beam-beam gas interactions, and multiply produced. The detectors with π^-–e^- separation abilities may be useful to reduce the BGs furthermore. Transition radiation detectors (TRD) may have a benefit for the purpose. It is composed of layers of radiators and X-ray detectors. The radiators emit soft X rays when charged particles are injected. The radiation efficiency for π^- is lower than that for e^- for 0.5 GeV$< p <$ 100 GeV, and the information may be used to discriminate π^-s over e^-s. The rejection efficiency of about 99% may be achieved for a total TRD width $\sim$ 50cm [14].

We have sketched a rough design for the detector. While the signal events have the well-defined kinematics and they might be discriminated from the BGs by such a detector, the signal event rate would be small and we need a long duration of the experiment. The performance of the detector must be studied very carefully, because the dominant part of the BGs must come from mis-measurements.

We have neglected the dependence of the DM velocity distribution in our neighborhood on the event rate in the above discussion. However, when the selectron decay width is small, the dependence cannot be neglected. When $E_{\rm beam} = \overline{E}_{\rm beam}$, the deviation of $\sqrt{s}$ from $m_{\tilde{e}^-}$ in the signal process is typically

$$\sqrt{s} - m_{\tilde{e}^-} \ \sim \ 10{\rm MeV} \times \left(\frac{\langle v_\parallel \rangle}{10^{-3}}\right)\left(\frac{\Delta m}{10{\rm GeV}}\right) \quad (7)$$

with $\langle v_\parallel \rangle$ the average of DM velocity along the beam axis. It is found from Eq. (4) that this value is comparable to or larger than the selectron decay width for $\Delta m/m_{\tilde{\chi}^0} \lesssim$ 10%. Thus, the DM velocity distribution affects the expected event rate when $\Delta m/m_{\tilde{\chi}^0} \lesssim$ 10%.

If the DM neutralinos are discovered in the electron accelerator experiment, we might constrain the DM velocity distribution by collecting the signal events. Since our DM direct detection in the electron accelerator needs several breakthrough technologies, it might be premature and speculative to discuss the measurement of the DM velocity distribution in addition to the DM detection. However, since technologies to measure the DM velocity distribution in the conventional DM detections are still limited, especially in cases of the small counting rate [15], the measurement of the DM velocity distribution using the electron accelerator might be considered as one of the alternative possibilities.

In the following we evaluate the averaged cross section assuming the spherically symmetric isothermal sphere

(SSIS) model for the DM velocity distribution. The DM velocity distribution in the rest frame of the earth is then

$$f_h(\vec{v})d^3v = \left(\frac{3}{2\pi\sigma_h^2}\right)^{3/2} e^{-\frac{3}{2}\frac{(\vec{v}+\vec{v}_{eh})^2}{\sigma_h^2}} d^3v. \quad (8)$$

We take the velocity dispersion of our local halo as $\sigma_h = 270$km/s. $\vec{v}_{eh}$ is the velocity of the earth with respect to the halo, and it is given as $\vec{v}_{eh} = \vec{v}_{es} + \vec{v}_{sh}$, with $\vec{v}_{es}$ and $\vec{v}_{sh}$ the velocities of the earth with respect to the sun and of the sun with respect to the halo, respectively. The solar system is moving toward the constellation Cygnus ((α, δ)=($21h12m01.053s$R.A., $+48°19'46.71''$decl.) (J2000.0) in the equatorial coordinate system) with speed $|\vec{v}_{sh}| = 233$km/s. The earth's speed in the orbital motion is $|\vec{v}_{es}| = 29.8$km/s [16]. The motion of the solar system generates the DM wind from the constellation Cygnus to the observers on the earth. When the beam axis is parallel (perpendicular) to the DM wind, $\langle v_\parallel \rangle$ is $\sqrt{\sigma_h^2/3 + v_{eh}^2}$ ($\sqrt{\sigma_h^2/3}$).

Being the experiments on the ground, the beam axis rotates around the the earth rotation axis. It leads to modulation of the event rate with a period a sidereal day ($23h56m4.09s$) due to the DM wind. Let us assume that the azimuth angle from south for the beam axis is θ and the experimental site is placed at latitude ψ. The angle between the beam axis and the direction of the DM wind, Θ, is modulated as

$$\cos\Theta = \cos\delta_\star \cos\delta \cos(t - \alpha - t_\star) + \sin\delta_\star \sin\delta \quad (9)$$

where $\sin\delta_\star = \cos\theta\cos\psi$ and $\sin t_\star = -\sin\theta/\cos\delta_\star$, and t is the local sidereal time at the experimental site.

In Fig. 1, the modulation of the cross section for the signal event during a sidereal day is presented in cases of $\delta_\star = 0°$ and $45°$. Here, $m_{\tilde{\chi}^0} = 100$GeV, $\Delta m = 10$GeV, and $E_{\rm beam} = \overline{E}_{\rm beam}$. The cross section averaged by Eq. (8) is reduced from that for the on-pole selectron exchange process ($\sim 12\mu$barn). The latitude for the experiment site ψ is assumed to be $0°$ for simplicity. The phases for $\delta_\star = 0°$ and $45°$ are not equal to each others when ψ is different from $0°$. (See Eq. (9).) Since δ is close to $\pi/4$, the amplitude of modulation in $\delta_\star = 45°$ is almost maximum. The maximum (minimum) point on the curve corresponds to a case that the beam is almost perpendicular (parallel) to the DM wind. The angle α can be inferred by the phase of the observed modulation. It might be difficult to constrain δ using a single beam line with a fixed energy due to the parameter degeneracy with $|\vec{v}_{eh}|/\sigma_h$. The degeneracy might be resolved by using two beam lines with different $\delta_\star$s. It is also possible to check the consistency of the observed DM wind with the astrophysical observation.

In the above, we assumed that the beam energy is tuned to $\overline{E}_{\rm beam}$. The measurement of the selectron and neutralino masses with precision of the order of or beyond an $O(10)$ MeV level in the future collider experiments might be challenging, but important for this experiment. This can be seen in Fig. 2, where the modulation of the signal cross section is presented in cases of

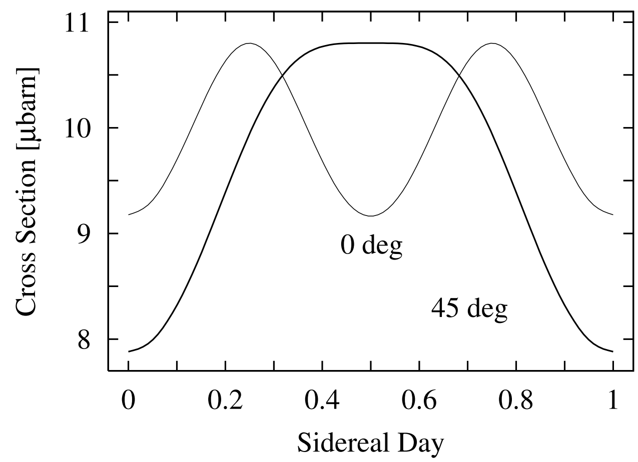

FIG. 1: Modulation of cross section for $e^-\tilde{\chi}^0 \to e^-\tilde{\chi}^0$ during a sidereal day for $\delta_\star = 0°$ and $45°$. Here, we take $m_{\tilde{\chi}^0} = 100$GeV, $\Delta m = 10$GeV and $E_{\rm beam} = \overline{E}_{\rm beam}$. Other astrophysical parameters are given in text.

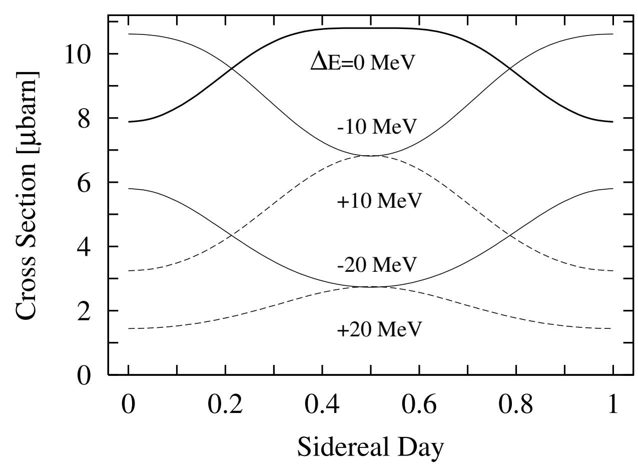

FIG. 2: Modulation of cross section for $e^-\tilde{\chi}^0 \to e^-\tilde{\chi}^0$ during a sidereal day for the beam energy $E_{\rm beam} = \overline{E}_{\rm beam} - 20$, -10, $+0$, $+10$, and $+20$MeV. Here we take $m_{\tilde{\chi}^0} = 100$GeV, $\Delta m = 10$GeV and $\delta_\star = 45°$.

$E_{\rm beam} = \overline{E}_{\rm beam} - 20$, -10, $+0$, $+10$, and $+20$MeV. The cross section reduces significantly once $|\Delta E| \gg 20$ MeV for the parameters. If the error of the mass difference is more than 20 MeV, one has to scan the beam energy to find the signals. The measurement of the beam energy dependence of the event rate might be useful to determine the $\overline{E}_{\rm beam}$, since the phases are reverse in the positive and negative energy deviation. Precise determination of $\overline{E}_{\rm beam}$ might allow us to interpret the event rate and determine the DM parameters. Especially, the measurement in the different beam energies may be used to resolve the parameter degeneracy between $\rho_{\rm DM}$ and σ_h in the observed event rate.

The SSIS model has two parameters, $\rho_{\rm DM}$ and σ_h, in addition to the velocity and direction of the DM wind.

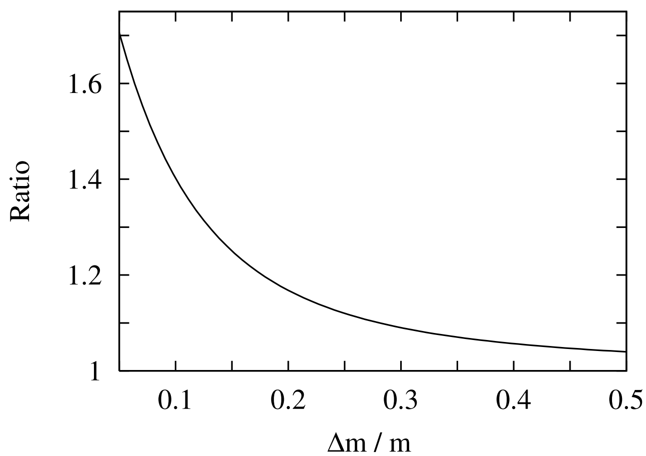

FIG. 3: Ratio of cross sections for $e^-\tilde{\chi}^0 \to e^-\tilde{\chi}^0$ in two cases that the beam axis is parallel and perpendicular to the DM wind, as a function of $\Delta m/m$. Here, $E_{\rm beam} = \overline{E}_{\rm beam}$.

We have seen that these might be constrained by changing the beam axis and/or beam energy in the electron accelerator experiment, though a sizable event number is required. We stress that it might be possible when the selectron decay width is suppressed by the selectron and neutralino mass degeneracy or the coupling (or the neutralino mixing) and it is comparable to the typical deviation of $\sqrt{s}$ from the selectron mass in the DM velocity distribution. In Fig. 3 we show a ratio of the cross sections in two cases that the beam axis is parallel and perpendicular to the DM wind as a function of $\Delta m/m$. Here, we use Eq. (5) for the selectron decay width. Larger $\Delta m/m$ makes two cross sections closer since the selectron decay width is increased. In this case, the modulation of the cross section becomes featureless.

The large-scale features of the flat rotation curves around galaxies are reproduced in the SSIS model. However, numerous dynamical arguments suggest that actual halo model may not be well described by such a distribution. In addition to the axisymmetric [17] and triaxial halo models [18], non-Maxwellian distributions, such as in the Sikivie caustic model [19], are proposed. The DM streams expected from the Sagittarius dwarf tidal stream might also affect the local DM velocity distribution [15]. It is important to measure the local DM velocity distribution, including the directional dependence, so that the models are discriminated. Our proposal might be applicable to it.

In this paper we discuss a possibility of neutralino DM direct detection through the scattering of local DM neutralinos with high intensity electron beam. The merit of the approach is that the DM can be identified as "the lightest neutralino" in direct and less ambiguous ways than the conventional DM detection experiments. Furthermore, the local DM density and velocity distribution might be constrained. However, to study the neutralino DM, the current of the electron beam must be $O(10)$ times higher than those currently planned, and the neutralino and selectron masses must be known very precisely at the level of precision expected in the future linear collider. In addition, the mass difference between them should be small to have a significant cross section. The experiment also requires the special setup to allow the long detector system along the beam line.

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[1] For reviews, G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996); L. Bergstrom, Rept. Prog. Phys. **63**, 793 (2000).
[2] C. L. Bennett *et al.*, Astrophys. J. Suppl. **148**, 1 (2003); D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **148**, 175 (2003).
[3] U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. D **68**, 035005 (2003); J. R. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, Phys. Lett. B **565**, 176 (2003); H. Baer and C. Balazs, JCAP **0305**, 006 (2003); A. B. Lahanas and D. V. Nanopoulos, Phys. Lett. B **568**, 55 (2003).
[4] For a review, J. R. Primack, Nucl. Phys. Proc. Suppl. **124**, 3 (2003).
[5] M. M. Nojiri, G. Polesello and D. R. Tovey, arXiv:hep-ph/0512204.
[6] M. Battaglia and M. E. Peskin, arXiv:hep-ph/0509135.
[7] S. Aminneborg, L. Bergstrom and B. A. Lindholm, Phys. Rev. D **43**, 2527 (1991).
[8] H. Bachacou, I. Hinchliffe and F. E Paige, Phys. Rev. D **62**, 015009 (2000); G. Weiglein *et al.* [LHC/LC Study Group Collaboration], hep-ph/0410364.
[9] J. A. Aguilar-Saavedra *et al.*, hep-ph/0106315.
[10] S. Hashimoto *et al.*, KEK-REPORT-2004-4.
[11] M. Tigner, Nuovo Cimento **37**, 1228 (1965).
[12] G.R. Neil *et al*, Phys. Rev. Lett. **84**, 662 (2000).
[13] K. Oide, in private communication.
[14] S. Eidelman *et al.* [Particle Data Group], Phys. Lett. B **592**, 1 (2004).
[15] B. Morgan, A. M. Green and N. J. C. Spooner, Phys. Rev. D **71**, 103507 (2005).
[16] M. J. Lewis and K. Freese, Phys. Rev. D **70**, 043501 (2004), and the references in it.
[17] N.W. Evans, Mon. Not. R. Astron. Soc. **260**, 191 (1993); M. Kamionkowski and A. Kinkhabwala, Phys. Rev. D

57, 3256 (1998).
[18] N. W. Evans, C. M. Carollo and P. T. de Zeeuw, Mon. Not. Roy. Astron. Soc. **318**, 1131 (2000).
[19] P. Sikivie, I. I. Tkachev and Y. Wang, Phys. Rev. Lett. **75**, 2911 (1995).
[20] The scheme may be called as energy recovery storage ring [13]. Naive estimation shows that the high frequency RF modes may be induced to cause energy losses.